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Final Report on the Joule-Scale Experimental Demonstration

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Disclaimer

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Final Report on the Joule-Scale Experimental Demonstration

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1. Executive summary

We describe the final results of the High Power Laser Pulse Recirculation project. We have developed and implementing a novel technique for picosecond, Joule-class laser pulse recirculation inside a passive cavity. The aim of this project was to develop technology compatible with increasing the efficiency of Compton based light sources by more than an order of magnitude. In year 1 of the project, we achieved a greater than 40 times average power enhancement of the mJ-scale laser pulses inside a passive cavity with internal focus. In year 2, we demonstrated recirculation of lasers pulses with energies up to 191 mJ at 532 nm, at a repetition rate of 10 Hz, and a pulse duration of 20 ps. In this high energy regime, we achieved up to 14 times average power enhancement inside the cavity. This enhancement factor is compatible with the new X-band based mono-energetic gamma-ray machine, Velociraptor, being constructed at LLNL. The demonstrated cavity enhancement is primarily limited by the poor spatial beam quality of the high power laser beam. We expect a nearly diffraction limited laser beam to achieve 40 times or better cavity enhancement, as demonstrated in low energy experiments in FY'07.

The two primary obstacles to higher average brightness and conversion efficiency of laser pulse energy to gamma-rays are the relatively small Compton scattering cross-section and the typically low repetition rates of Joule-class interaction lasers (10 Hz). Only a small fraction (10^{-10}) of the available laser photons is converted to gamma-rays, while the rest is discarded. To significantly reduce the average power requirements of the laser and increase the overall system efficiency, we can recirculate laser light for repeated interactions with electron bunches. Our pulse recirculation scheme is based on nonlinear frequency conversion, termed recirculation injection by nonlinear gating (RING), inside a passive cavity.

The main objectives of the two year project were:

1) Validate the concept of RING pulse trapping and recirculation technique. *Completed Sep. '07*
2) Develop cavity designs compatible with a laser-electron Compton light source. *Completed January '08.*
3) Demonstrate trapping and recirculation of laser pulses suitable for high brightness gamma-ray generation. *Completed Aug. '08*

Our project has established RING as a viable technology for enhancing Compton scattering based gamma-ray generation. With sufficient funding we can implement pulse recirculation on the next generation Mono-energetic Gamma-Ray machine under construction at LLNL.

2. Introduction

Isotopic identification with nuclear resonance fluorescence (NRF) is a key enabling technology for the Department of Homeland Security. This approach to detection of special nuclear material (SNM) yields very low false positive and false negative counting rates, minimizes the dose required for cargo interrogation, and does not activate the target. A high average brightness gamma-ray flux is required for rapid, high fidelity measurement. The aim of the ongoing Strategic Initiative (SI) at Lawrence Livermore National Lab (LLNL), Thomson Radiated Extreme X-Rays (T-REX), is to develop a monochromatic, narrowband, high brightness gamma ray source based on Compton-scattering high power laser photons with accelerated electron bunches from a linac.

A primary obstacles to generating a high brightness gamma-ray flux is the relatively small Thomson scattering cross-section. As a result, high brightness Compton sources require high power Joule-class lasers which are costly and complex. Since only a small fraction ($\sim 10^{-10}$) of the incident laser photons is converted to gamma-rays, recirculation of the laser pulse would increase both the gamma-ray flux and the efficiency of the Compton light source.

Under the High Power Laser Pulse Recirculation project we have developed and implemented a novel technique for picosecond, Joule-class laser pulse recirculation inside a passive cavity. The aim of the current project was to develop technology compatible with increasing the efficiency of Compton based light sources by more than an order of magnitude.

Our laser pulse recirculation technology is based on nonlinear conversion inside a passive cavity. The canonical layout of our recirculation cavity is shown in Fig. 1. The incident laser pulse at the fundamental frequency passes into the cavity through a dichroic mirror. A nonlinear crystal efficiently frequency doubles the incident pulse. The 2nd harmonic pulse then becomes trapped inside the cavity since the dichroic mirrors are highly reflective at 2ω and highly transmissive at 1ω. This pulse recirculation concept, termed RING (Recirculation Injection by Nonlinear Gating), is compatible with high power ultrashort pulses because the nonlinear phase accumulation is sufficiently low to allow hundreds of cavity roundtrips without distorting the spatial and temporal pulse profiles. Because RING cavity does not require active stabilization and consists of only a few components, it is highly robust and can be deployed in hostile environments.

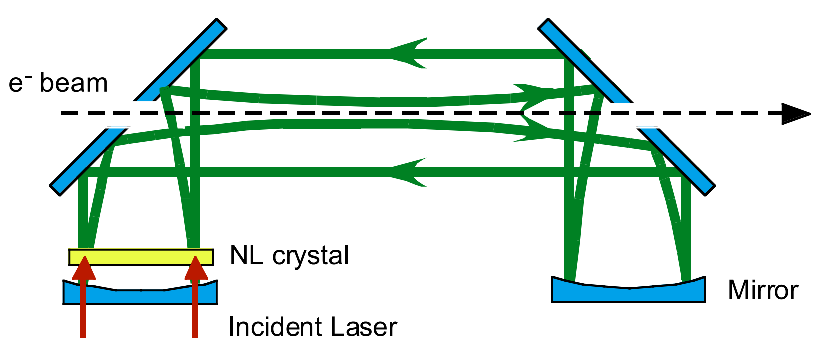

Fig. 1: Conceptual layout of the RING cavity integrated with the electron beam

In year 1 (FY07) of the project we demonstrated over 40 times average power enhancement for a tapped low energy (500 μJ) laser pulse. In year 2 of the project, we recently achieved our milestone result: RING cavity recirculation of a joule-scale laser pulse.

In this report we will discuss the results of our joule-scale laser pulse trapping experiment.

Prior Work

We note key aspects of RING cavity design, completed in FY07:

1) Cavity contains an internal focus. The interaction between the electrons the photons would occurs at the cavity focus.
2) Cavity is self-imaging. A beam inside the cavity is imaged back onto itself after two roundtrips. This minimizes diffraction losses and allows recirculation of aberrated beam profiles.
3) The number of interfaces within the cavity is minimized to decrease the optical losses per cavity roundtrip.

The experimental cavity design is shown in Fig. 2. It consists of two concave spherical mirrors spaced twice the focal length apart, forming a confocal resonator. A nonlinear crystal (BBO) acts as a nonlinear switch converting incident 1ω pulse to 2ω. The cavity mirrors are dichroic: highly transmissive at 1ω, allowing the incident pulse to enter the cavity, and highly reflective at 2ω, trapping the frequency doubled pulse inside. The radius of curvature of the incident beam is adjusted using a lens telescope to produce a collimated beam wavefront inside the resonator. On subsequent cavity roundtrips, the green beam focuses to cavity center when propagating from right to left and is collimated when propagating from left to right. This RING design incorporates requirements necessary for scaling to recirculation of joule-class pulses. Our design is simple, robust, and allows for future integration with a linac.

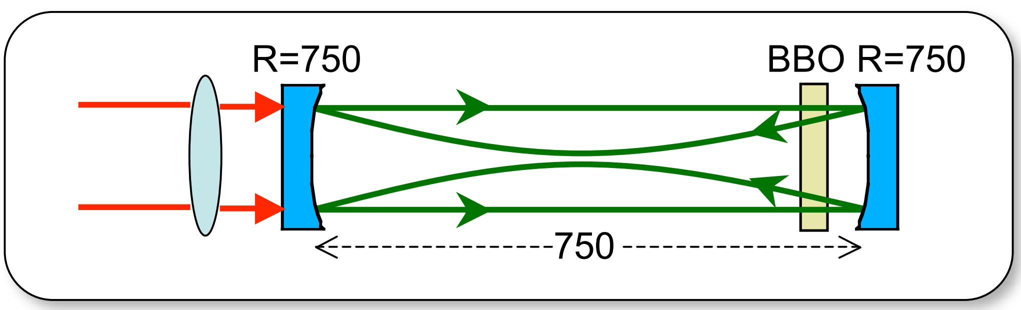

Fig. 2: Experimental cavity design

Our constructed cavity was placed under vacuum, as shown in Fig. 3. The crystal phasematching angle, the cavity length, and the tip/tilt of the two mirrors were remotely controlled by vacuum compatible actuators. The chambers were kept at a pressure in the range of 10^{-3} torr to minimize nonlinear phase accumulation and prevent laser induced gas breakdown. This cavity was set-up in the Advanced Petawatt Concepts Lab at LLNL. The incident laser pulse was produced by an OPCPA laser system operating at 1053nm, at 10Hz repetition rate and generated ~2.5 mJ of IR in a pulse chirped to 10 ps.

Cavity performance was evaluated by measuring the ring-down signal after the resonator. Since the dichroic mirrors are 99.8% reflective, 0.2% of the 2ω light leaks through the end mirrors after each roundtrip. This signal is then measured by a photodiode and a high bandwidth oscilloscope. A sample ring-down signal is shown in Fig. 4. The cavity enhancement for this signal is 49. The enhancement factor is calculated by dividing the area of all the pulses in the pulse train by the area in the initial pulse. Since the area under the pulse is proportional to its energy, the resulting cavity enhancement factor is a measure of the average power enhancement.

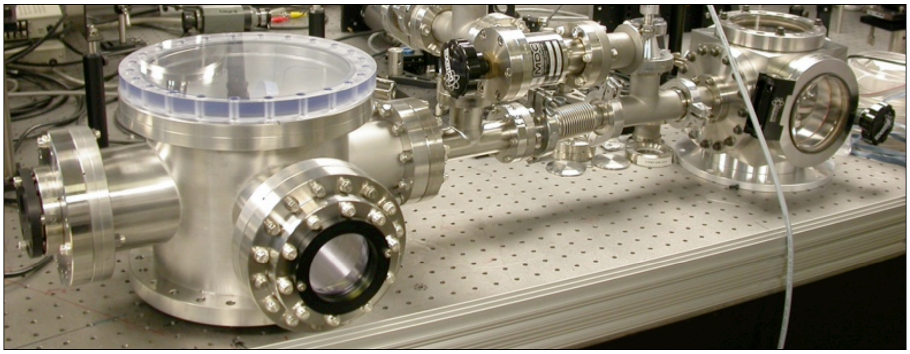

Fig. 3: Constructed low energy RING cavity

The pulse separation is equal to the cavity roundtrip time, which is twice the cavity length or ~5 ns, as confirmed by measurement show in the inset to Fig. 4.

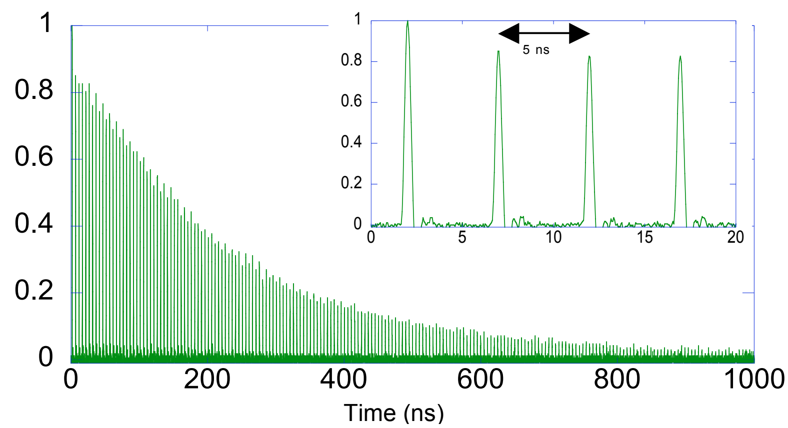

Fig. 4: Sample low energy RING down-signal. Cavity enhancement 49x

The highest trapped energy at 532 nm achieved in FY07 was 500 μJ. The ring-down signal reached at that energy is shown in Fig. 5.

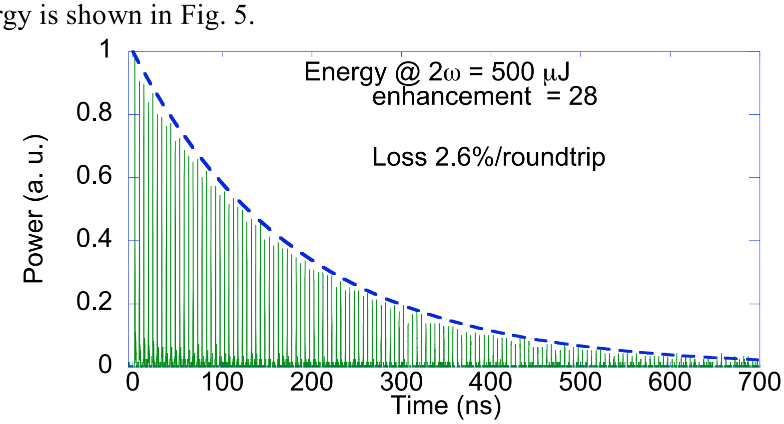

Fig. 5: Ring down signal fitted with a best-fit signal decay curve.

The cavity enhancement here is 28. The signal decay curve shows a 2.6% loss per cavity roundtrip.

High Energy RING Cavity

Considering RING recirculation of high energy versus low energy pulses, major differences consist of

1. Absorption induced thermal deposition on the nonlinear crystal and cavity mirrors.
2. Optical damage due to higher laser intensity and fluence.

To mitigate optical damage, the diameter of the incident laser beam is increased to lower peak laser intensity and fluence. Our design of the joule-scale RING cavity (Fig. 6), is identical to the low energy with the exception of 2” diameter cavity mirrors and a large aperture nonlinear crystal to accommodate increased beam size. The cavity shown in Fig. 6 was ray-traced using FRED software package.

We used either a 20x20x1.2 mm BBO crystal (the largest aperture available for BBO) or a 30x30x6 mm DKDP crystal. Our simulations (Fig.7), confirmed by the experimental observations, showed that the increased thermal load on the crystals was acceptable at our power levels (~10W/pulse). In Fig. 7, the maximum temperature difference versus the average recirculating power is calculated for several crystals. The limiting power of the recirculating green energy is ~300W for DKDP and ~600W for BBO. We define recirculating power as (cavity enhancement) x (per pulse energy at 2ω) x (repetition rate).

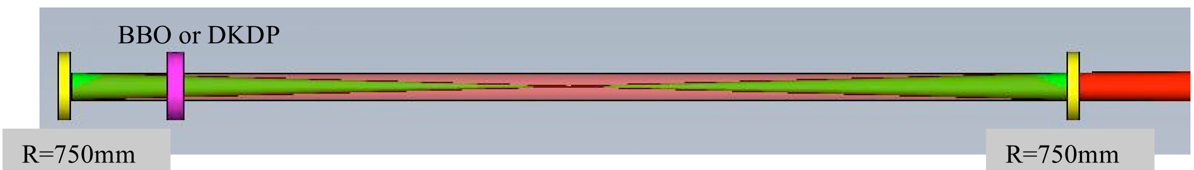

Fig. 6: High energy RING cavity layout

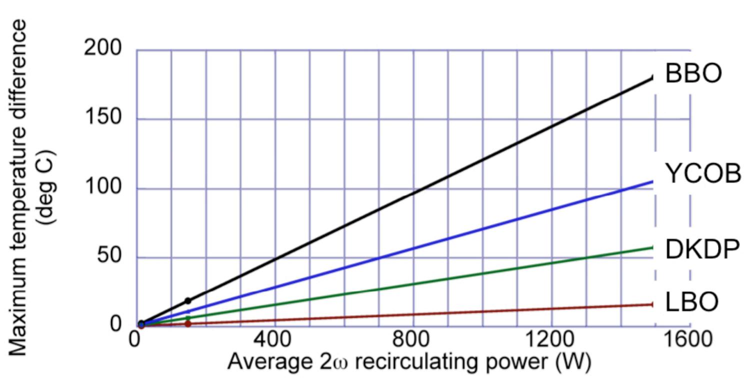

Fig. 7: Maximum temperature difference vs average recirculating power for several nonlinear crystals

Here, the mirrors are better than 99.8% reflective at 532 nm, and the AR crystal coating is better than 99.7% transmissive. The two 2” diameter mirrors form a confocal resonator. The spacing between the two mirrors is slightly greater than 750 mm, because the refractive index of the crystals is greater than unity. The cavity length is $L_{cavity} = L + \Delta L$, where L=750 mm, and $\Delta L = L_c(1 - 1/n_c)$, where L_c is the crystal thickness and n_c is the crystal refractive index. L_{cavity}=751.91 mm for DKDP and L_{cavity}=750.43 mm for BBO.

The laser for the joule-scale experiments is provided by a state of the art interaction laser system (ILS) developed under T-REX SI for Compton-based gamma generation. This system produces up to 800 mJ of compressed 1064 nm laser pulses at 10 Hz repetition rate. The high energy RING was built to be mobile, capable of being moved among different locations and facilities. The photos of the constructed set-up are shown in Fig. 8. The optics are placed inside two vacuum chambers and the full assembly is mounted on a 2’x4’ transportable optical table. The pressure inside the chambers reaches 10^{-3} torr range. The cavity was placed next to the ILS laser in the linac cave of B194 for experiments.

Fig. 8: RING cavity assembly

The beam paths are traced out in Fig. 9. The leakage signal after the RING cavity is indicated by light green. The dichroic mirrors after the cavity filter out residual 1ω light. The photodiode then measures the ring-down signal.

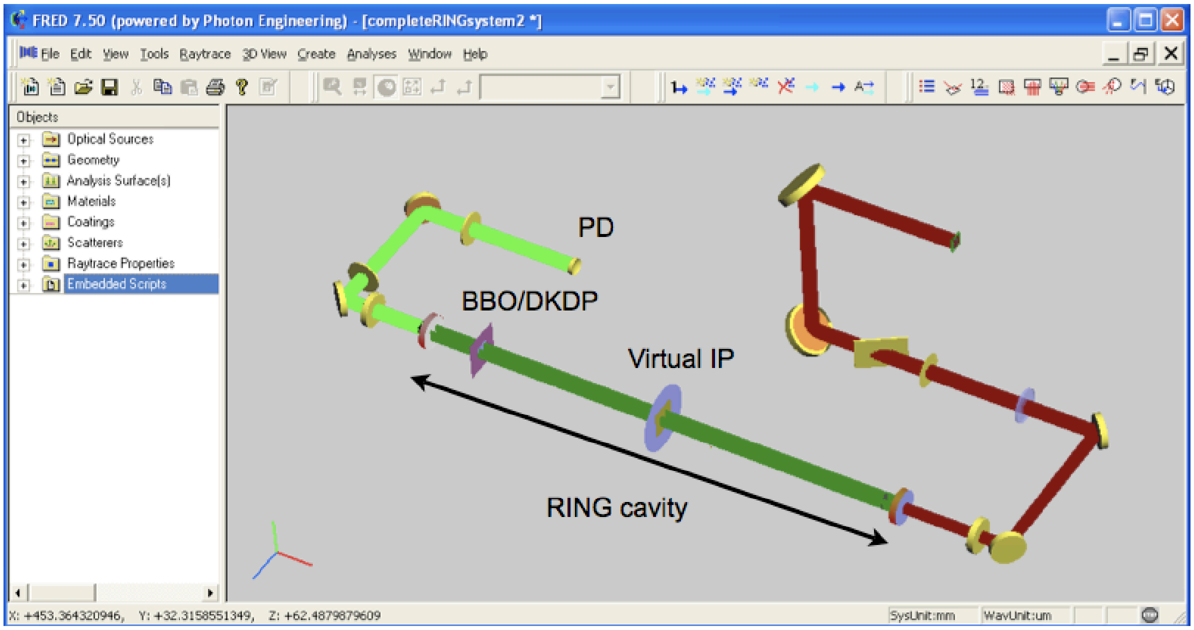

Fig. 9: Layout of the RING experiment

High Energy RING Experimental Results

The highest energy at 532 nm trapped inside the RING cavity was 191 mJ. The peak obtained energy was limited by the available energy and intensity of the ILS laser. In our experiment, we used two different nonlinear crystals for laser pulse trapping: 1.2 mm thick, 20x20 mm aperture BBO crystal, cut for Type I phasematching, and 6 mm thick, 30x30 mm aperture DKDP crystal cut for Type II phasematching. With the DKDP crystal, we trapped a maximum of 177mJ at 532nm and achieved cavity enhancement of 14. With the BBO crystal, we trapped a maximum of 191 mJ at 532 nm and achieved cavity enhancement of 11. The results of the experiment are summarized in Table 1.

	Input	1.2 mm BBO	6 mm DKDP
Center λ (nm)	1064	532	532
Maximum Energy per Pulse (mJ)	750	191	171
Cavity Enhancement		11	14
Duration (FWHM)	20% in 20ps		
rep-rate (Hz)	10	10	10
Loss/roundtrip		0.25	0

Table 1: Summary of high energy RING experiment

The RING cavity enhancement is calculated by measuring the cavity ring-down signal. Leakage light at 2ω escapes through the end mirrors after each roundtrip. Dichroic mirrors are used to filter out residual 1ω light from the signal. The ring-down signal is then measured with a fast photodiode (EOT Inc, Biased Silicon Detector, ET-2030 1.2 GHz, <300ps rise time) and a 6 GHz oscilloscope (Tektronix TDS6604B) to resolve the closely spaced pulses. A sample signal from the RING cavity is shown in Fig. 10. The pulses are sampled at a resolution of 50 ps/point. The pulses are separated by approximately 5 ns, a measure of cavity roundtrip time. The signal is normalized to 1 at its peak. The decrease in the peak signal with successive roundtrip indicates cavity loss due to diffraction, reflection, scattering, and absorption. The area under each pulse recorded by the photodiode on the oscilloscope corresponds to the energy in the laser pulse after each roundtrip. Cavity enhancement is then calculated by dividing the total area of the waveform by the area of the first pulse. Note that the photodiode signal drops below zero. These additional waves are an artifact of the measurement and are caused by impedance mismatch.

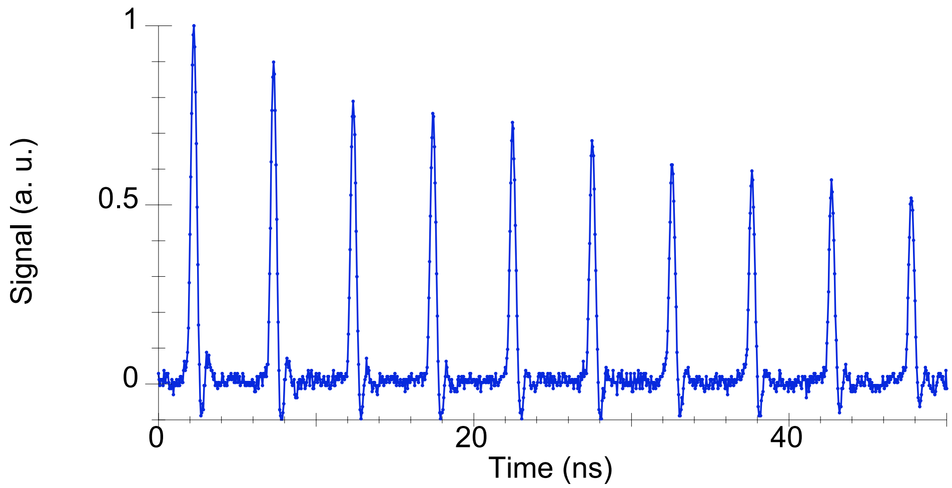

Figure 10: Ring-down signal inside a DKDP RING cavity

Next, Fig. 11 shows the ring-down signal from a DKDP cavity, where the trapped energy at 532nm is 177 mJ. Approximately 50 roundtrips are resolved. We calculate cavity enhancement to be 14 for this signal.

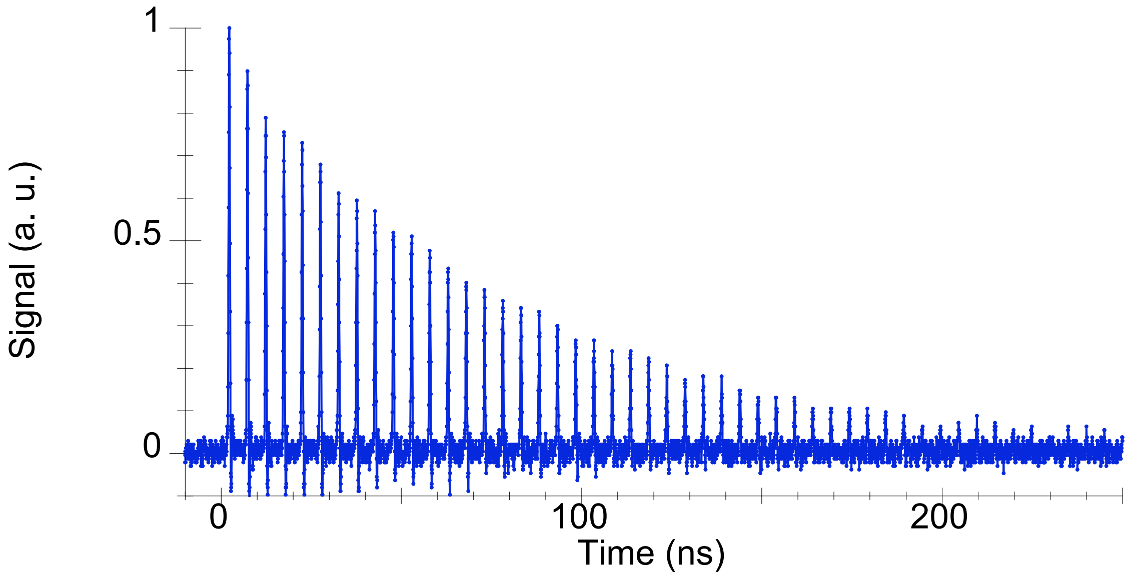

Figure 11: Full ring-down signal inside a DKDP RING cavity. Trapped energy at 532nm is 177mJ and total cavity enhancement is 14.

Fig. 12 shows the cavity ring-down signal for a BBO cavity. Here, the loss per roundtrip is higher and fewer cavity roundtrips are resolved. The cavity enhancement here is 11. The cavity enhancement for a BBO cavity is lower due to the smaller aperture of the BBO crystal. Because the laser beam profile is highly aberrated, a significant portion of the beam diffracts. The crystal then acts as an aperture stop and a smaller aperture crystal causes higher diffraction losses.

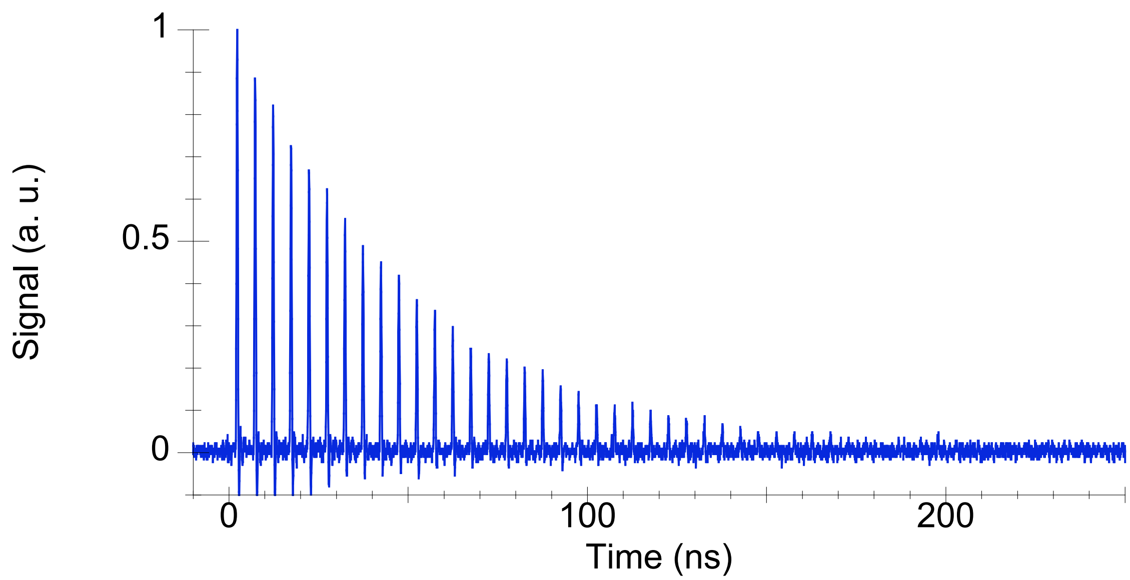

Figure 12: Full ring-down signal inside a BBO RING cavity. Trapped energy is 191mJ, and total cavity enhancement is 11.

We can determine the loss per roundtrip by fitting a power-law curve to the data. If we assume transmission of T_0 per roundtrip, then the energy after n roundtrips is T_0^n. The loss per roundtrip is $(1-T_0)$. Fig. 13 and 14 show the results for DKDP and BBO, respectively. For the DKDP cavity the roundtrip loss is 7% and for the BBO cavityt it is 9%.

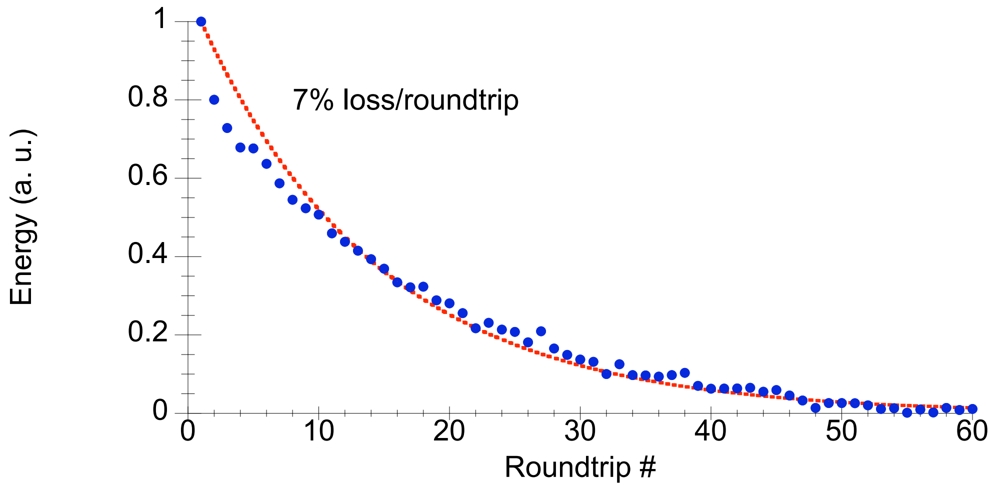

Fig. 13: Energy vs roundtrips for DKDP cavity. Experimental data (blue circles) is fitted by a T_0^n curve (dashed red line), where T_0=0.93

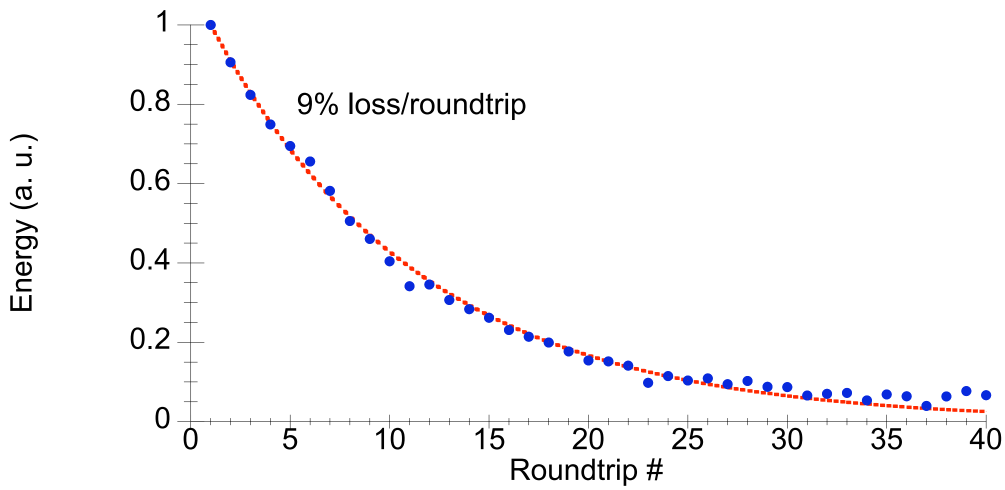

Fig. 14: Energy vs roundtrips for BBO cavity. Experimental data (blue circles) is fitted by a E=T_0^n curve (dashed red line), where T_0=0.91

Discussion of High Energy results

The cavity enhancement for the high energy RING cavity (11-14) is lower than cavity enhancement for the low energy RING cavity (28-49). The lower cavity enhancement is most likely caused by the poor laser beam quality of the ILS laser, and is not limited by the energy of the trapped pulse. The ILS laser beam is highly aberrated and the main loss is primarily due to diffraction of the highly aberrated beam within the cavity. In Fig. 15, we measured cavity enhancement of the BBO and DKDP cavities for a range of trapped energy values.

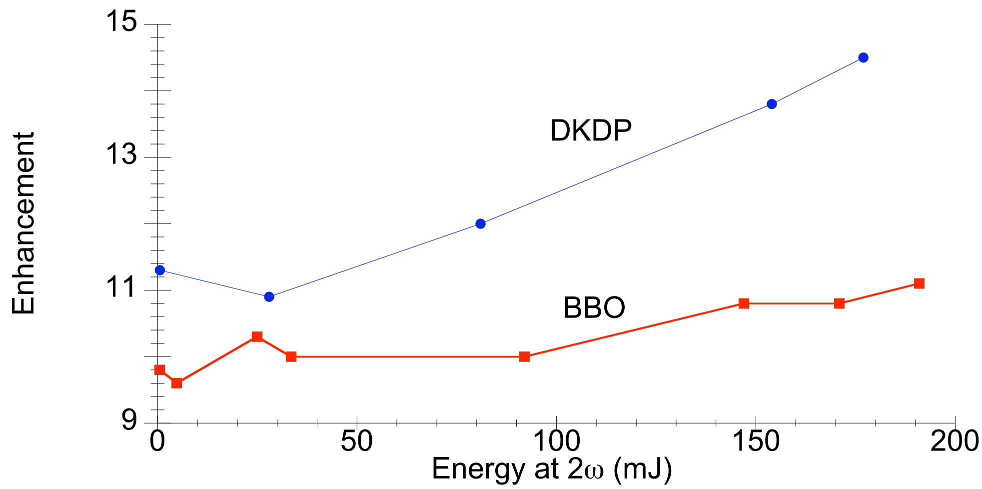

Fig. 15: Cavity enhancement for BBO (red squares) and DKDP (blue circles) cavities for various trapped energies of the 532nm ILS laser pulses.

There is no degradation in cavity enhancement with increased energy. The data implies that the performance of the RING cavity is not limited by the energy of the trapped laser pulse. We anticipate that using a good spatial quality laser beam will result in joule-scale cavity enhancement > 40, same as measured using the low energy OPCPA laser in the Advanced Concepts Petawatt Lab in FY'07.

We have measured the ILS beam, shown in Fig. 16. The CCD image shows a highly elliptical beam with some high frequency spatial modulation. Using a Shack-Hartmann wavefront sensor we verified that beam ellipticity is caused by astigmatism.

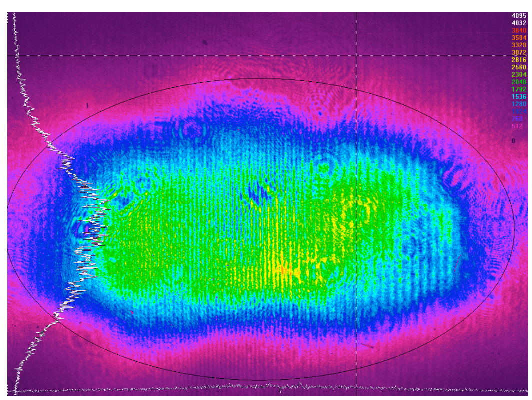

Fig. 16: Incident IR beam into the RING cavity. The beam has approximately 2:1 aspect ratio and high spatial frequency modulation.

The upconverted green beam, shown in Fig. 17, is also highly aberrated. The significant spatial aberration of the beam prevents proper cavity alignment. The leakage green beam is shown in Fig. 18. This is an integrated image of all the cavity roundtrips. Here, we observe two spatial modes offset from each other. This corresponds to two different paths that the beams take through the RING cavity. High spatial aberration results in increased scattering and diffraction losses.

We experimentally verified that beam aberrations reduce cavity enhancement. We used an iris before the RING cavity to set the maximum beam diameter. With the iris partly closed, we expect the cavity enhancement to increase since the aberration over a central portion of the beam are less severe than over the full beam. We used a low energy beam and a DKDP RING cavity. The cavity enhancement with the iris fully open (Fig. 19a) was 11 as compared to 18 with the iris partly closed (Fig. 19b).

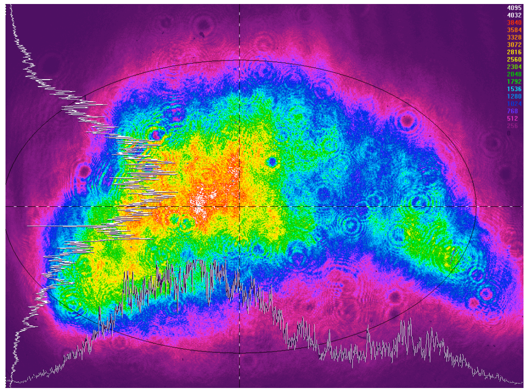

Fig. 17: Upconverted 2ω beam after the nonlinear crystal

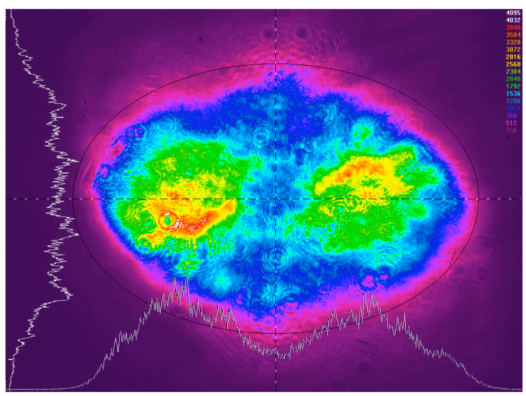

Fig. 18: Green beam after the RING cavity

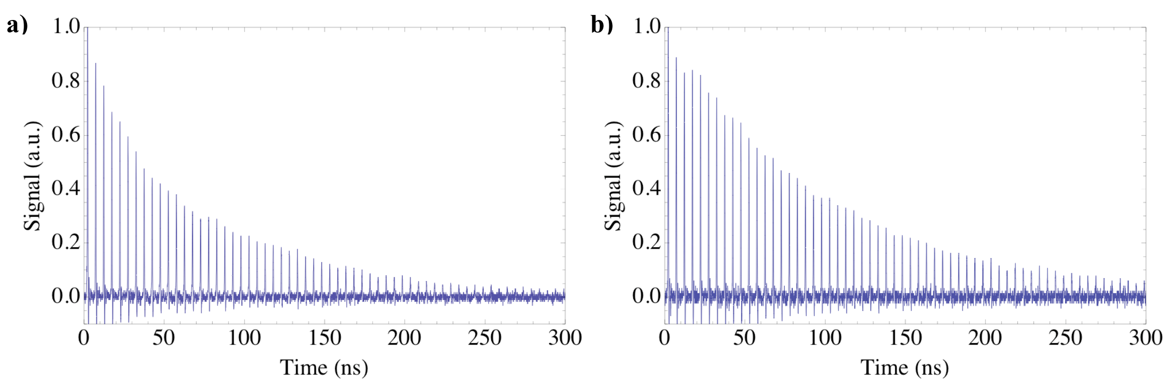

Fig. 19: Ring –down signal for (a) open iris and (b) closed iris. The cavity enhancement, is for (a) 11 and (b) 18.

Another undesirable effect that we noted was some snapping of the laser beam inside the RING cavity. This was audible at near full laser power (> 150 mJ of green). We believe that this problem results from stray laser scattering. A likely mechanism, is that rays that are reflected rather than transmitted through the crystal focus at a different location inside the cavity. After several roundtrips, these scattered rays focus near some surface causing breakdown. These effects should be minimized with:

1) Better incident beam profile
2) Better quality anti-reflection (AR) coating on the nonlinear crystal.
3) A slight wedge on the crystal to walk off the reflection from the cavity.

In our analysis of the RING cavity we also noted that wavefront aberrations inside the cavity rapidly degrade the quality and location of the focal spot. As an example (Fig. 20), just a $1/20^{th}$ of a wavelength power aberration quickly degrades the quality of the focal spot. This would rapidly reduce the number of gamma-rays produced with each roundtrip.

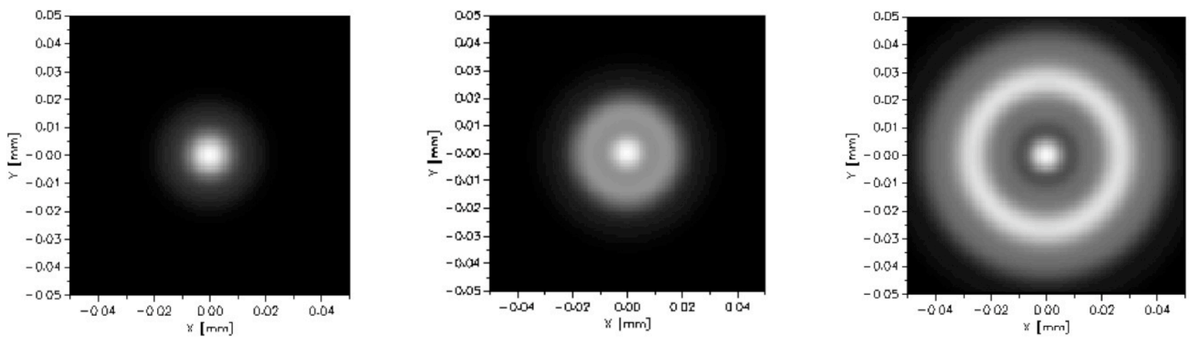

Fig. 20: Focal spot profile inside an aberrated RING cavity after (a) 1, (b) 50, (c) 100 roundtrips. One of the optics has a $\lambda/20$ @633nm power aberration.

Since, in practice, obtaining a 1/10 of a wavelength peak-valley wavefront quality 2" optic is challenging, a spatial wavefront compensating optic is required. We propose to make a spatial phaseplate to statically correct the aberrations on the beam after each roundtrip. Magnetorheological finishing (MRF) is a promising technique that has been used extensively at LLNL to produce wavefronts as good as lambda/30. This technique could be adapted to RING cavity to increase the cavity enhancement and boost the flux of the generated gamma-rays.

Summary

We have successfully met our milestone results for NA-22 sponsored Picosecond Pulse Recirculation Project. We demonstrated up to 14 times cavity enhancement with a trapped 171 mJ green pulse. Better spatial quality laser beam should result in cavity enhancements up to 40, similar to the low energy results.

The main remaining issue is improving the wavefront beam quality to allow better than 10 times enhancement of the gamma-ray flux. We believe that the experimentally demonstrated performance of the RING cavity will allow better than an order of magnitude enhancement in gamma-ray flux.